

VIBRATION ANALYSIS OF NONLINEAR CONICAL SPRING BRACING SYSTEM SUBJECTED TO SEISMIC LOAD

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ABSTRACT

In this study, an attempt has been made to assess the impact of proposed nonlinear conical spring bracing (NCSB) system on seismic response subjected to earthquake. The developed system includes of two telescopic conical spring springs that operate in axial compression. Due to shape of spring, the proposed system can performed as a nonlinear stiffness element that provide more lateral stability to structural frame. The action of NCSB does not control the low and moderate vibration due to earthquake but it acts for severe vibration whereas the frame displacement pass the allowable boundary. This inconstant performance avoids excessive effects of conventional bracing system if they attached as retrofitting components to moment resistant steel frame. by other words, due to the aforementioned characteristics of NCSB system, the inherent ductility of steel frame is not scarified and earthquake energy can be dissipate due to frame ductility, but, NCSB system provided more stability of structures and prevent large story drift. In this study, pushover and time history analyses has been conducted to evaluate the seismic performance of introduced device. The results from pushover disclose a considerable enhancement of structural capacity and ductility. Besides, the application on NCSB device changed the location of plastic hinge formation in structural elements. Furthermore, time history results proved the efficiency of NCSB device on reducing the maximum displacement.

KEYWORDS

Dynamic analysis, earthquake records, pushover analysis, nonlinear conical spring bracing, plastic hinge formation, ductility.

INTRODUCTION

Vibration impacts due to dynamic loads such as earthquake, wind and etc., can induce an unnecessary structure oscillations which may cause to catastrophic collapse. Improvement of structural performance subjected to dynamic loads is the most important concern in structural engineers, experts and researchers. The aforementioned enhancement shall consider the structural stability (safety) and economical design feasibility. It means that, the appropriate design technique especially choice of vibration control device is the most imperative issue to prevent the structure from any vibration induced failure. The prior earthquake design approach was based on inherent ductility of structures to dissipate the imposed earthquake energy. This practise was considered as the most feasible and safe design. But it may lead to unrealistic design and structural damage. A lot of research has been focused on supplementary energy dissipation devices which are installed in structures. Whereas these devices don't belong to main structural system can be offered as external energy dissipation system which can be easily substituted after severe excitation (Tsu T Soong and Dargush 1997). Vibration control techniques n can be categorized into three main types: active control (Yao 1972), passive control and semi active control. Passive control methods were introduced at the earliest stage, and were used commonly in seismic design procedure due to the minimum maintenance cost. Table 1, briefly presents the seismic control system which has been introduced in a few studies.

Active variable stiffness (AVS), a system for structural control has absorbed numerous attentions and interests. The desire effects and improvement of the structural performance in earthquake excitation of AVS systems were proven by previous studies(Takuji Kobori et al. 1993)(Yang, Wu, and Li 1996) Such a system has been investigated experimentally with implementation in full-scale building in Japan(T Kobori and Kamagata 1992). Most of available variable stiffness system are operated using external electrical controller which might cause delay in system performance. These systems are highly depended on energy recourse and also need repetitive maintenance. Variable stiffness bracing system is developed as retrofitting system for steel structures which included of four leaf springs in series with wire rope cable which its totally fabricate without dependency to electrical supply (Fateh et al. 2015)(Hejazi, Jaafar, and Fateh 2014).(Dct 2009) focused on the nonlinear behavior of the spring that could be achieved by varying the mean spring diameter in axial direction. In Conical

springs we have some advantages compared to cylindrical springs. In non-telescoping springs, the coils stack one above the other during compression. Another advantage of the conical springs can have a higher sideways stability, so they will better resist buckling. (Dct 2009).

Table 1 Seismic control systems

Vibration Control System	
Passive energy dissipation system	<ul style="list-style-type: none"> • Metallic yield damper(Tyler 1985)(Scholl 1990)(T T Soong and Spencer Jr 2002) • Friction damper(Pall et al. 1993) • Visco- elastic dampers(Crosby, Kelly, and Singh 1994)(Moliner, Museros, and Martínez-Rodrigo 2012) • Visco-fluid damper (Arima et al. 1988)(Rama Raju, Ansu, and Iyer 2014) • Tuned mass damper(Fujino and Abé 1993)(Soto and Adeli 2013) • Tuned liquid damper(Tamura et al. 1995)(Georgakis 2011) • Rubber bearing Base isolation system(Naeim 1999) • Friction Pendulum Bearings(Wang, Chung, and Liao 1998)(Mosqueda, Whittaker, and Fenves 2004)
Active Control System	<ul style="list-style-type: none"> • Active Mass Damper Systems(Yamamoto et al. 2001) • Active Tendon Systems(Bossens and Preumont 2001) • Active Brace Systems(Cheng, Jiang, and Lou 2010) • Active coupled building systems(Christenson et al. 2003) • Pulse Generation Systems(Cheng, Jiang, and Lou 2010) • Distributed actuators(Fisco and Adeli 2011)
HybridControl System	<ul style="list-style-type: none"> • Hybrid Mass Dampers(Saito, Shiba, and Tamura 2001) • Hybrid Base-Isolation System(Yang, Danielians, and Liu 1991) • Hybrid Damper-Actuator Bracing Control(Cheng and Jiang 1998)
Semi-active Control System	<ul style="list-style-type: none"> • Semi-active Tuned Mass Dampers(Hrovat, Barak, and Rabins 1983) • Semi-active Tuned Liquid Dampers(Banerji et al. 2000) • Semi-active Friction Dampers(Chen and Chen 2004) • Semi-active Vibration Absorbers(T T Soong and Spencer Jr 2002) • Semi-active Stiffness Control Devices(Patten et al. 1998) • Electrorheological Dampers(Makris et al. 1995) • Magnetorheological(MR) dampers(He, Huang, and Liu 2010)(Dyke et al. 1996) • Semi-active Viscous Fluid Damper(Symans and Constantinou 1995) • Piezoelectric dampers(Preumont et al. 2008)

The new bracing system with Nonlinear Conical Spring system was developed as adaptive structural control system to protect the building against severe vibration and ground movement. NCSB system includes nonlinear leaf springs which induce nonlinear and Nonlinear Conical Spring capacity at different frame displacement. The Nonlinear Conical Spring system (NCSB) system does not scarify the energy dissipation characteristics and ductility capability of moment resistance frame. For large vibration amplitudes, the bracing member and nonlinear spring acting and restrain unacceptably large storey drift. So, the braced frames can display ductile performance which is dissipating seismic energy.

DEVELOPMENT OF NCSB DEVICE

NCSB device installation in frame is shown in Figure 1. Once the frame subjected to dynamic force such as earthquake excitations, it sways to left and right and NCSB device intends to move to the right and left. Due to dual action of NCSB and compression resisting of conical spring, the induced force form vibration transfer to the device by cables. Since the cable is buckling free element, the force can be easily transfer to the main device in unlimited cycle. The action of NCSB can be divided to two main phases include solid telescopic conical spring and cable actions. For more explanation, whenever the device reaches to maximum deflection of conical spring, the cable stiffness adds to system stiffness since it works as braces which fixed at both ends. The 3D schematic model is presented in Figure 2.

The details of NCSB elements layout is describe in Figure 3. The NCSB device comprises of a nonlinear solid conical spring bracing attached to a cable to counter the dynamism of the force resulted from the vibration on the structure of a building The nonlinear conical spring bracing device further comprising, of a rectangular

frame having an exterior clumper (label 1) at each vertical side of the rectangular frame. A telescopic conical spring (label 2) attached at each end of the rectangular frame at the exterior clumper (label 1). Furthermore a steel rail (label 3) fixed at middle of the rectangular frame. An interior clumper (Label 4) attached to each telescopic conical spring (label 2), the cylindrical core (label 5) is slidable along the steel rail (label 3) and a steel rod (label 3) passes through each end of the rectangular frame and the interior clumper (4) and ended at the middle of the cylindrical core (label 5).

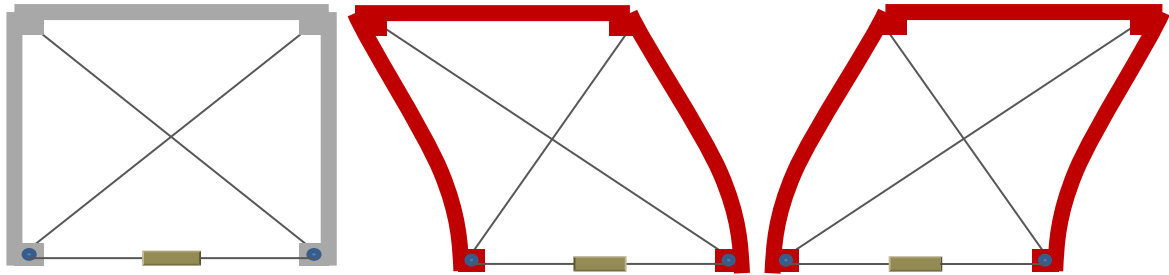


Figure 1 NCSB Installation and action in frame

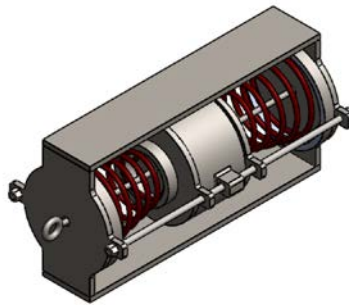


Figure 2 3-D schematic view of NCSB

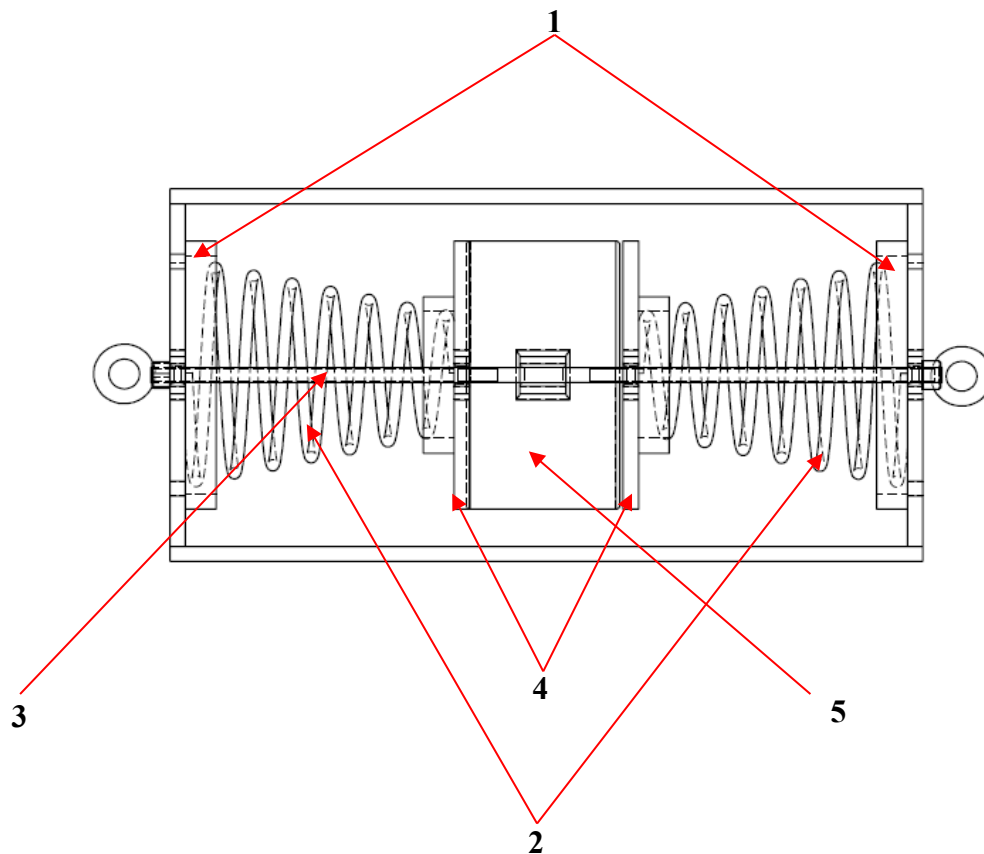


Figure 1 NCSB elements' layout

DYNAMIC EVALUATION OF NCSB IN DEVELOPED ARCS3D

The mathematical model of NCSB has been implemented in developed web based software called as ARCS3D which is abbreviated of Analysis of Reinforced Concrete Structure-3D. The push over and time history analysis of reinforced concrete (RC) structures furnished by NCSB device performed for 5-story building. More over the results compared with bare frame and efficiency of NCSB application has been discussed. The compressive concrete strength grade for both pushover and time history analyses are considered as 35 MPa. The columns and beams are modeled with same geometry sizes of 300 X 300 mm as shown in Figure 4. The diameter of reinforcement bars and concrete cover to steel bars are assumed 20 mm and 35 mm respectively in all the cases. In addition to, the story height and bay width for all models are 3 and 5 m correspondingly.

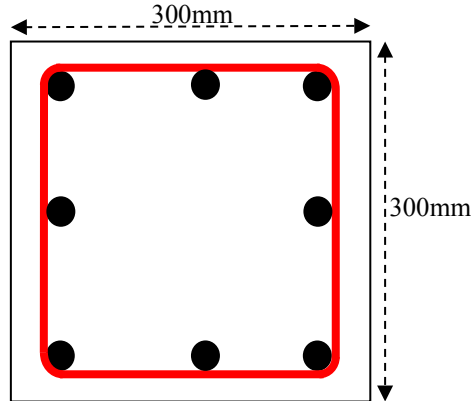


Figure 4 beams' and columns' sections

RESULTS AND DISCUSSIONS

Pushover Analysis

Pushover analysis is conducted for frame equipped with and without NCSB device as presented in Figure 5. The NCSB spring wire's diameter and spring's length are equaled to 8 and 120 mm respectively. The biggest and smallest diameters of conical spring considered as 400 and 150 mm. Furthermore, the diameter of wire rope cable equals to 10mm with high strength steel material. Results from pushover analysis for both models are reported in Figure 6. As can be observed, the implementation of NCSB device caused to increase the pushover capacity by 68 % and reached to 455 KN and also the ductility characteristic of frame furnished by NCSB enhanced. In addition to, the locations of plastic hinge formation in structures are monitored and presented in Figure 7. In the bare frame the plastic hinge initially formed at base nodes at columns then extended to upper columns. But, once the NCSB applied, the locations of plastic hinges altered and moved into the device around 61%.it means NCSB implementation in frame not only increase the structure capacity and ductility but also reduce the plastic hinge formation in structural components and shift them in NCSB device.

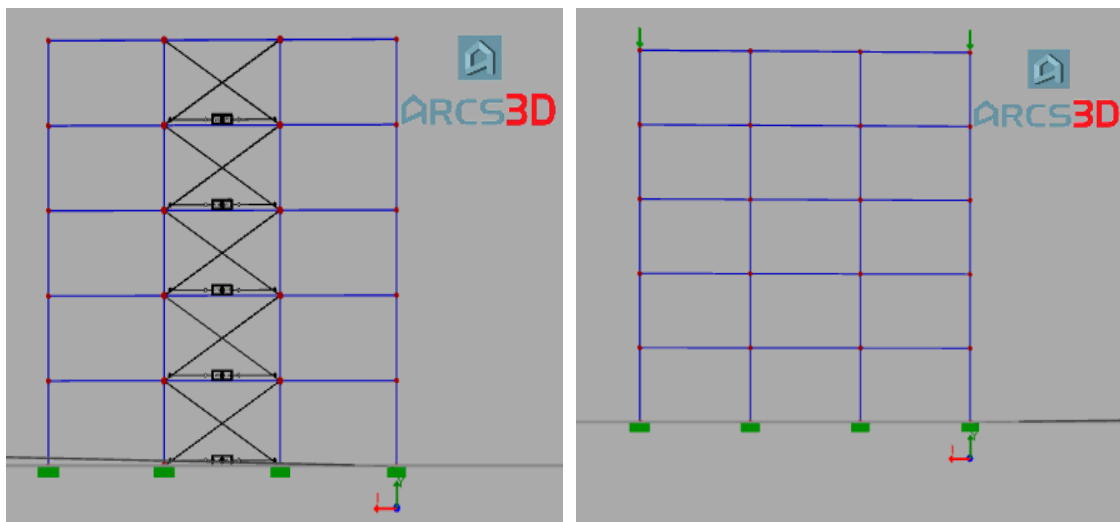


Figure 5 Pushover models in ARCS3D

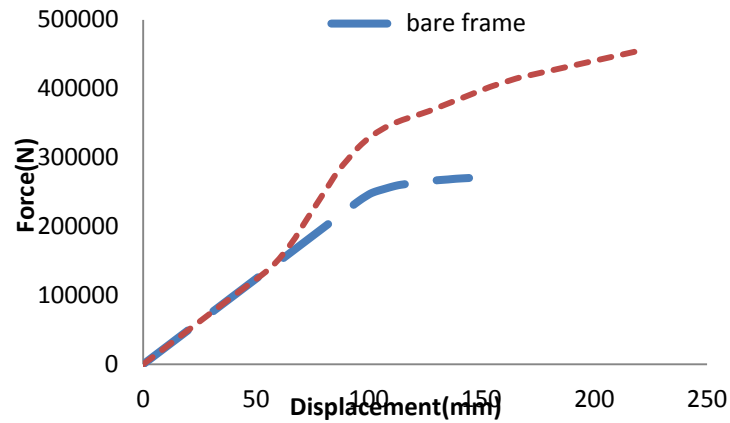


Figure 6 Push over curve for frame with and without NCSB system

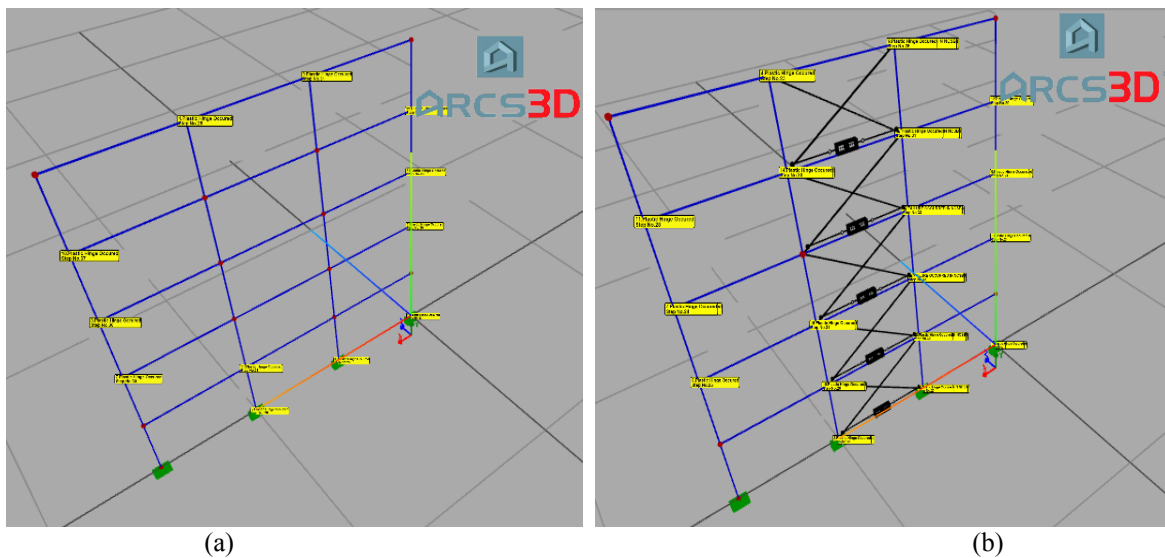


Figure7 Location of plastic hinge formation at (a) bare and (b) NCSB frames

Time History Analysis

Time history analysis for bare and NCSB subjected to El-Centro North-South (1940) as shown in Figure 8, is conducted with developed finite element program. The 5-story models are analyzed with and without NCSB system. All beams are subjected to the equal 50Kn/m distributed loads. Moreover, 100KN point loads are applied at all columns as illustrated in Figure 9. The results reported in terms of time history of top node displacement. Figure 10 shows the displacement change verse time of considered top nodes in both models. As can be observed, application of NCSB device in frame caused to reduce the maximum absolute displacement about 35%.

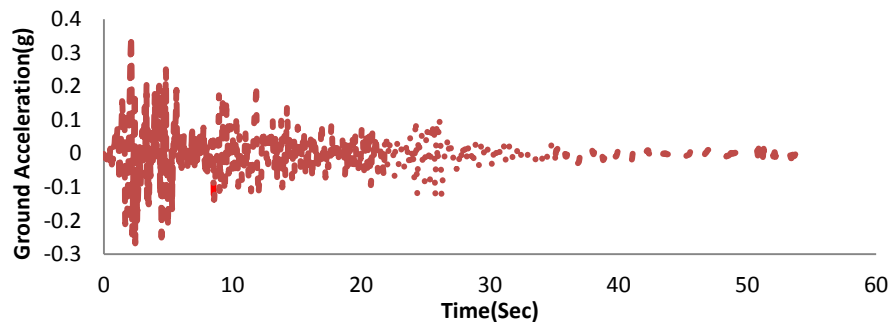


Figure 8 El-Centro Earthquake (1940) acceleration North-South record

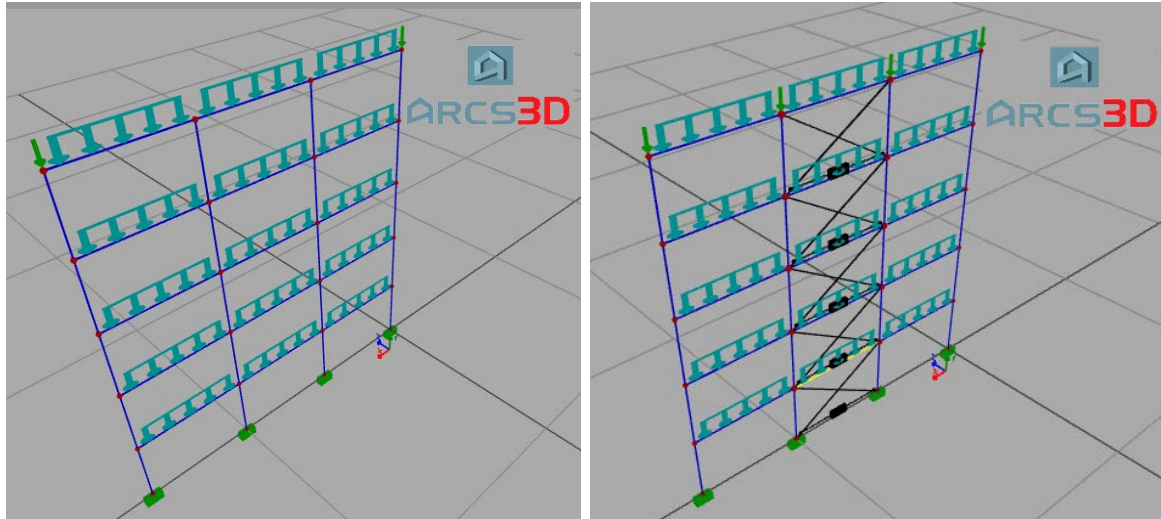
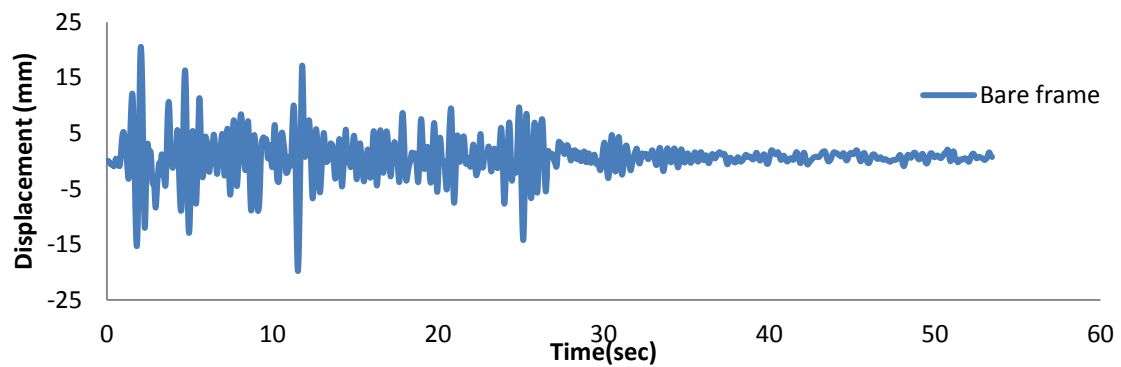
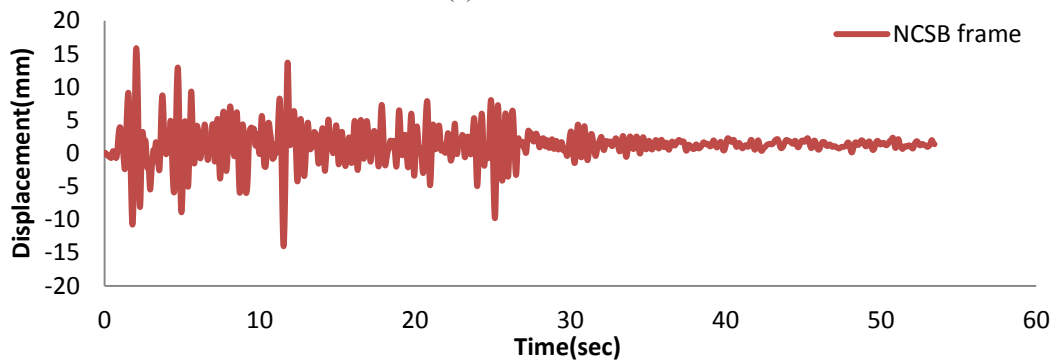


Figure 9 Pushover models in ARCS3D



(a) Bare frame



(b) NCSB frame

Figure 10 displacement response histories under El-Centro earthquakes

CONCLUSION

This study introduced a rapid retrofitting technique for frame structures. Nonlinear conical bracing system comprised of two telescopic solid conical springs which are attached to wire rope cables. NCSB device can be applied as a new rapid retrofitting practice due to simplicity of NCSB fabrication and installation process in high ductility frame. Moreover it can be used as supplementary lateral resisting element in new framed building. Push over and time history analyses of 5-story RC frame with and without NCSB device has been performed. The results from push over analysis reveal the efficiency of NCSB device in structure. Not only the capacity and ductility characteristics of frame enhanced but also, the location of plastic hinge formations altered from main structural elements and shifted in NCSB device as supplementary energy dissipation system. Furthermore, time history analysis reports a considerable reduction of maximum displacement value.

For future study, finite element simulation is extremely essential to assess the NCSB ductility performance under monotonic displacement. Besides, the experimental dynamic test must be conducted to evaluate the seismic response of aforesaid method in reality by use of pseudo dynamic actuator or shaking table.

ACKNOWLEDGEMENT

This work received financial support from the Ministry of Science, Technology, and Innovation of Malaysia under Research Project No. 5524254. This support is gratefully acknowledged. The NCSB system is under filling patent grant at Malaysia intellectual property organizations (MyIPO).

CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this paper.

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